DESIGN, CONSTRUCTION, TEST AND FIELD SUPPORT OF A CONTAINERLESS PAYLOAD PACKAGE FOR ROCKET FLIGHT

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FINAL REPORT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Process Engineering Laboratory
George C. Marshall Space Flight Center

SPACE SCIENCES LABORATORY
GENERAL ELECTRIC
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1.0 INTRODUCTION AND SUMMARY OF EXPERIMENT REQUIREMENTS

The Electromagnetic Containerless Processing Package (ECPP), designed and fabricated under contract NAS8-30797, was used to conduct experiment 74-48 in the NASA Marshall Space Flight Center space processing SPAR sounding rocket program on December 14, 1976 at the White Sands Missile Range. This report summarizes the work done under contract NAS8-30797 and is the final report for that contract.

The ECPP is capable of the performance of a wide variety of micro-gravity experiments on containerless processing of metals and alloys aboard a sounding rocket. This first implementation of the electromagnetic positioning and heating technique as a sounding rocket experiment payload incorporates an RF induction heater utilizing the same coil for heating as is used for the application of weak positioning forces during solidification. The coil is configured so that the magnetic field vanishes at the specimen position in the center of the coil and increases uniformly in all directions away from this position. Specimen position errors are detected through the effect on the impedance of the coil as the specimen moves away from the reference position into higher field regions. These error signals are differentiated and utilized in a closed loop position control servo which removes any initial specimen kinetic energy and brings the specimen to the reference position with a vanishing final velocity error. Containerless melting and solidification of metals, alloys and semiconductors allows consideration of the achievement of large amounts of supercooling in freely floating melts by elimination of sites for heterogeneous nucleation on crucible walls which enables the performance of new experiments in grain refinement of metals and alloys.

The requirement which was assigned to the ECPP for experiment 74-48 was the performance of the tasks listed below during 360 seconds of 0-g a sub-orbital sounding rocket flight. With minor modifications the apparatus can be considered for application to a number of other containerless melting and solidification

experiments or for experiments to study properties of superheated containerless melts or for evaporation studies.

a. Electromagnetically, at radio frequency, heat to melting an approximately 0.9 cm diameter sphere of beryllium with dispersed beryllium oxide without physical contact with the molten material.

b. After melting, allow the approximately 0.9 cm diameter sphere of beryllium to solidify, again without physically contacting the material while it is molten.

c. Provide an electrical signal indicative of the temperature of the beryllium sphere.

d. Provide photographs of the beryllium sphere during the heating, melting and cooling periods with such photographs being obtained solely by the light emitted by the sphere.

2.0 DESCRIPTION OF ECPP

2.1 Components within the ECPP

The ECPP is a completely self-contained and, during flight, a self-sufficient device which heats conductive materials as an induction furnace does and, in the weightless or 0-g condition of free fall, provides electromagnetically induced forces which keep the material being heated in the center of the work coil. A description of the principles upon which the operation and design of the ECPP are based may be found in references 1, 2 and 3. The ECPP requires only a voltage placed upon one of the pins of its connector to initiate its sequence of operations. The apparatus contains the following items.

a. A silver-zinc battery, nominal voltage 30 volts, capable of providing approximately 12 ampere-hours of electrical charge

b. A radio-frequency power generator, which draws 1200 watts DC from the battery and produces radio-frequency current at 107 kHz

c. An impedance matching transformer which provides the high current needed in the work coil

d. A work coil (see Figure 1) inside a pressure-tight stainless steel chamber which heats the material placed within it and provides the force to guide the material back to the center of the coil if it should move significantly from the center of the coil. Pressure is monitored by solid state pressure sensor (0 to 20 psia).

e. A supply of water in a closed circulating system powered by a small gear pump

f. A camera with color film to record the image of the material by the light the material emits after it has been heated

g. A pyrometer to indicate the temperature of the material being heated

h. An electronics box which controls the apparatus

i. A low voltage power supply which supplies power to operate the circuits in the radio-frequency power generator and in the electronics box

j. An enclosure of aluminum 3.2 mm thick which serves as the main structural support for the apparatus and, also, serves to prevent radiated radio-frequency power from leaving the interior of the apparatus.

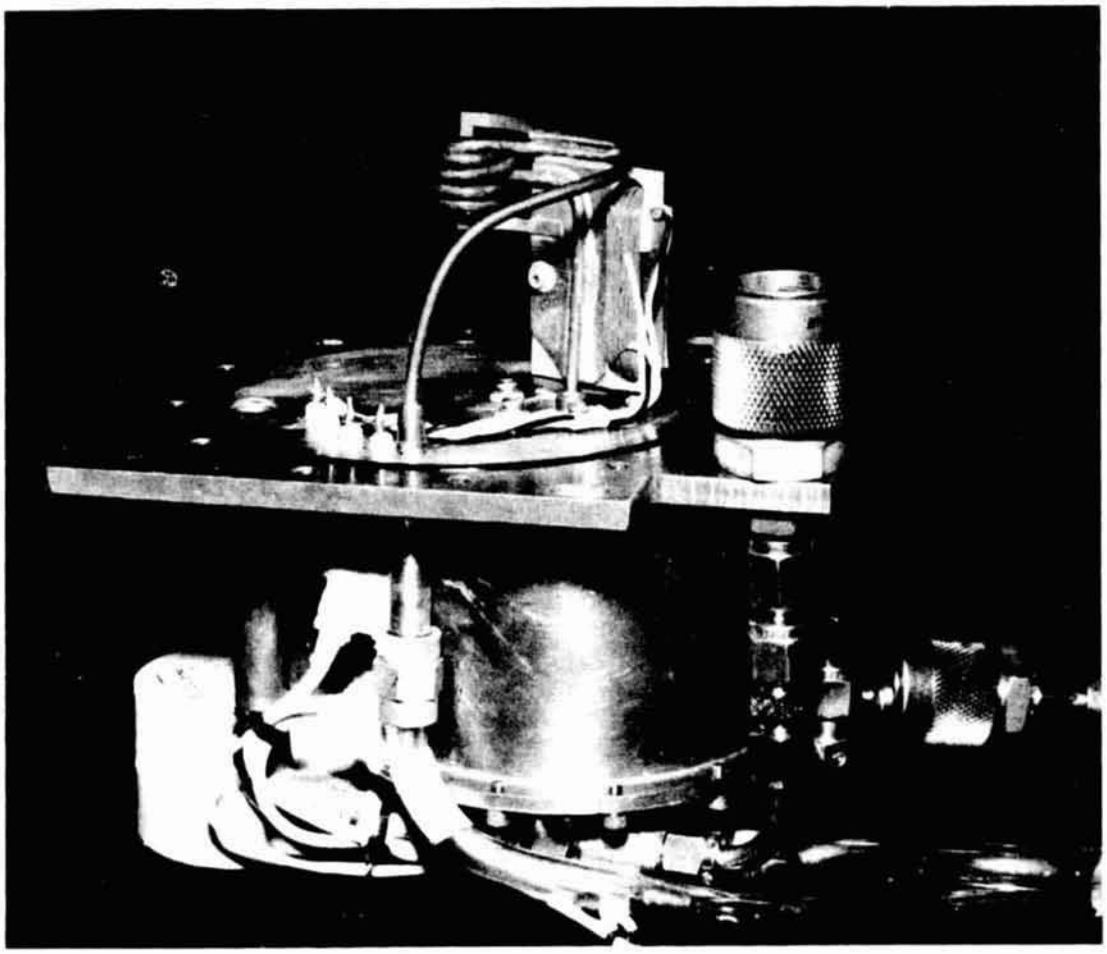

Figure 1. Work Coil and Matching Transformer

During ground testing, a control panel is required to monitor the sequence of operations going on within the ECPP and to over-ride,as necessary, actions initiated within the ECPP.

The ECPP apparatus, as shown on drawings 95M17100 and 95M17150, as well as in Figures 2 and 3 of this report, is a right circular cylinder 58.4 cm long by 35.6 cm clearance diameter. One end (the top) contains threaded holes also on a 33.02 cm bolt circle diameter spaced 15° apart. The threaded holes contain 10-32 inserts. The bottom surface of the apparatus, the side which is intended to be used for mounting to the rocket, has a circular pattern of through 5.2 mm diameter mounting holes spaced 15° apart on a 330.2 mm (13.00 inch) diameter. The thickness of the bottom plate is 0.32 cm (1/8 inch). The flight ready package weighs 42 kg with the C.G. located within one cm of the geometrical center of the ECPP.

Access panels are located on opposite sides of the package; one is 43.2 cm by 22.9 cm and the other is 28 cm by 15.9 cm. The upper edge of the 43.2 x 22.9 cm panel is 0.6 cm from the top of the ECPP, and the 28 x 15.9 panel is 14.6 cm from the top. A vertical plane bisecting both panels contains the experiment package center line and the center of a mounting hole at the top and bottom. Access to the inside is required for

1. Process Chamber Removal/Installation
2. Battery Removal/Installation
3. Work Chamber preparation/Installation
4. Removal/refilling of coolant and drying cooling system for shipment/storage
5. Battery Connect - Disconnect
6. Camera Film Magazine.

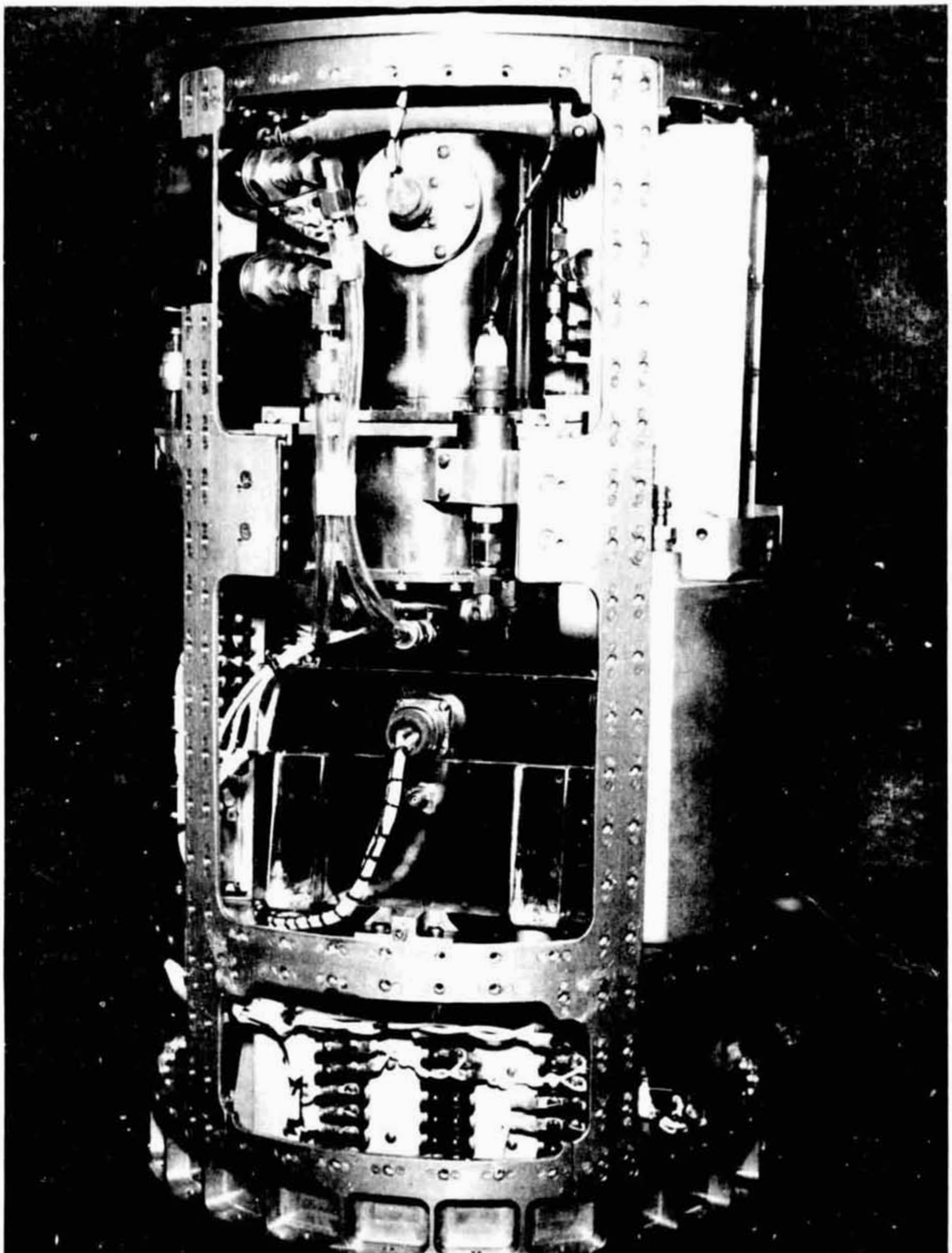

Figure 2. Electromagnetic Containerless Processing Package
(Outer skin removed)

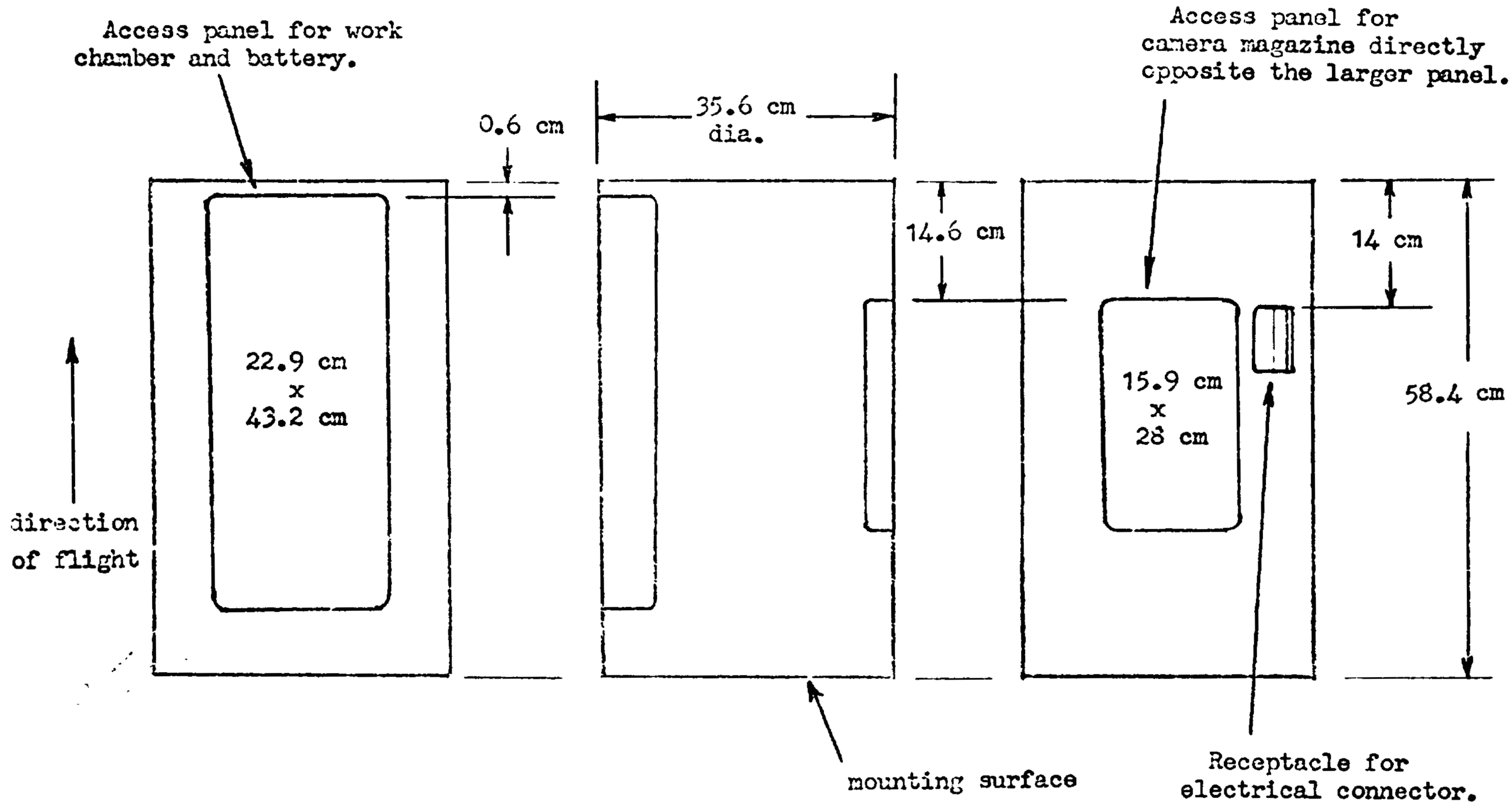

Figure 3. Access Panels and Connector Locations

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Except for the camera film magazine, all above access is through the larger panel. The electrical connector for input and output signals is located in a recess near the smaller access panel.

2.2 Interface with Rocket

The ECPP power amplifier delivers about 600 watts of RF power at 100 KHz to the processor chamber coil. Because of this high level, several design features were implemented to avoid any difficulties in interfacing with the rocket program systems. The RF Power Amplifier is enclosed in a metal box designed to reduce radiation leakage. The processor coil is located completely within the metal processing chamber and its matching transformer is totally enclosed, which also minimizes leakage. These steps lower the RF level within the experiment sufficiently that the internal circuits operate normally and all lines leaving the experiment can be adequately filtered. The outer envelope of the ECPP is RF tight and of sufficient thickness to attenuate the radiation to levels below MIL-STD-461A. If all power had been drawn from the battery supplied on the rocket to provide electrical power to the experiment, the high ripple current from the ECPP class "B" RF Amplifier would have been extremely difficult to adequately filter. The DC current required by the ECPP is 43 amperes, and at that current the required attenuation would have needed a very large filter to meet MIL-STD-461A. By using an internal battery the large ripple current was confined within the ECPP and was effectively shielded by the ECPP outer enclosure.

The launch signal line and its return operate a relay coil and are completely isolated from all circuits within the ECPP. The internal battery ground is floating relative to the chassis and was brought out separately. A third return for telemetry was brought out through a 2000 ohm resistor so that if it is required in a differential telemeter input it cannot cause large circulating ground currents if grounded at some point other than at the unit point ground. The chassis is fully floating from all circuits and is also isolated from the work coil and its matching transformer

where RF currents greater than 250 amperes exist. Also, all lines exiting the ECPP do so through an "L" filter so that the RF that may be picked up inside the ECPP will not be able to leave the package.

2.3 Qualification Tests

The ECPP was subjected to several environmental tests, which it successfully passed. These tests are summarized below and have been reported in detail in Qualification Test Data for ECPP, SSL-ECPP-010.

2.3.1 - Shock - One shock was given, longitudinally, in the direction of flight, according to the following spectrum.

100 Hz	30g
100-2000 Hz	+6.5 dB/octave
2000-4000 Hz	750 g

$Q = 10$

2.3.2 - Vibration - The following sinusoidal vibration was applied along the longitudinal axis and along two mutually perpendicular axes.

10- 24 Hz	0.075 inch, peak-peak
24-110 Hz	2.3 g, peak
110-500 Hz	5.3 g, peak

sweep rate - 3 octaves/minute

The following random vibration was applied along the same three axes.

20 Hz	0.023 g^2/Hz
20-1000 Hz	+1.8 dB/octave
1000-2000 Hz	0.230 g^2/Hz

2.3.3 - Temperature - The apparatus, without the silver-zinc battery, was operated at 50°C and at 10°C.

2.3.4 - Vacuum - The apparatus was operated as the pressure in the vacuum chamber was decreasing from 0.1 torr to 0.01 torr.

2.3.5 - Electromagnetic Emission - The apparatus was operated while the electromagnetic radiation emanating from it was measured. The radiation was found to be within specification limits for tests CE02, CE04 and RE02 administered according to MIL-STD-1541 and MIL-STD-461A, Notice 3. Details of the electromagnetic emission test may be found in the EMI Test Report, ECPP-006-1.

3.0 OPERATION OF ECPP

When a voltage signal is sent to the apparatus, it is activated and, after a predetermined timed interval, the power generator provides its maximum power to the work coil. After the elapse of another predetermined interval, the power to the coil is reduced to a level which permits the specimen to cool rapidly while still providing sufficient force to keep the specimen in the center of the coil. At the end of another predetermined interval of time, intended to be just before the end of the "0-g" period, the entire apparatus is turned off. The lengths of these timed intervals are variable and, for experiment 74-48, were nominally 50, 100 and 350 seconds, respectively, for a total experiment "on time" of 500 seconds. The execution of these timed intervals is irrevocably begun once the initial activation signal is received by the ECPP.

The ability of the apparatus to heat a specimen placed in its work coil depends upon the resistivity of the material. For the ECPP the ability to heat a 0.92 cm diameter specimen is a maximum at an electrical resistivity to 50 t0 100 micro ohm-cm and the ability to heat is less for any other value of resistivity. The time required to heat a material to a specific temperature depends upon the thermal properties of the material in addition to the electrical resistivity, which, in turn, depends upon the temperature of the material. The maximum temperature

attainable also depends upon the total emissivity of the material but an estimate of the maximum temperature which can be attained can be based upon the electrical resistivity of the material at that temperature. The following table provides such estimates.

Electrical Resistivity (micro ohm-cm)	Maximum Temperature (deg Celsius)
30 - 200	1500
15 - 350	1390
7 - 600	1280
3 - 800	1160

The maximum temperatures given in the preceding table have been calculated by assuming a total emissivity of 0.5 but for smaller values of emissivity higher temperatures may be achieved and, conversely, for greater values of emissivity the maximum achievable temperatures will be lower than listed. For example, a sphere of tungsten, heated in the breadboarded, prototype ECPP was observed to reach a maximum temperature of 1944°C. For experiment 74-48 an emissivity of 0.4 was expected with a resistivity of beryllium at its melting point of approximately 80 micro ohm-cm from which, using the table above with the input power to the specimen reduced by a factor of 2/3 (as explained, below), a temperature of 1420°C was calculated. This is approximately the temperature actually achieved.

Details of the ECPP interface requirements with the SPAR rocket are given on drawing 95M17150 and in the Interface Control Document for the ECPP, SSL-ECPP-009.

4.0 EXPERIMENT DESCRIPTION AND FLIGHT RESULTS

Complete details of experiment 74-48 may be found in the SPAR Experiment 74-48 Quick Look Analysis, issued jointly by the General Electric Co. and Kawecki-Berylco Industries on January 14, 1977 and in the final report for contract NAS8-31963, Containerless Processing of Beryllium. The goals of this experiment were

(1) Satisfactory melting and solidification of the specimen.

(2) Improved cast microstructure in the specimen.

(3) Improved properties of the specimen material.

The ECPP was operated aboard a sounding rocket during the period of free fall on December 14, 1976 at the White Sands Missile Range and accomplished the containerless melting and resolidification of a beryllium oxide dispersion in beryllium. The following table shows the time of occurrence of major events as read from the telemetry record. Times are measured in seconds from launch.

t (sec)	Event
0	Launch signal
50.5	Positioning and melting power on, specimen oscillations noted
85.9	First reading from solid state pyrometer as the specimen began to glow
94	Solid state pyrometer reached maximum reading, nearly in saturation
121.3	Shape oscillation, completion of melting
139.4	Power reduction (33%), battery voltage increase
159.7	Initiation of low power, positioning mode
169	Attainment of low power mode

At 85.9 seconds, the onset of self-luminescence of the specimen at a dull red growing to bright orange followed by a rapid change of shape of the specimen to a deformed shape caused by electromagnetic field forces in the high power mode was reported by the ECPP via telemetry and by means of the movie camera, which recorded the image of the specimen by means of its radiated light. Viewing of the

movie film revealed no discernible motion of the specimen except as noted above. The stability of the specimen position during the entire time it was hot enough to be luminous is remarkable since such steadiness was never fully achieved in the laboratory due to small vibrations of the laboratory itself. The only motion noticed in the specimen during the entire movie record with the specimen hot enough to be luminous is the shape change and slight shape oscillation at the moment of complete melting.

Following the completion of melting, the specimen began superheating to the point at which the radiation loss equalled the total input power. Due to the loss of one of the power amplifiers at 139.4 sec, the total power input to the specimen was reduced, after melting, from approximately 69 watts to approximately 46 watts which, it has been calculated, would have provided a superheat of 116 C deg above the melting point of 1284°C, or 1400°C.

The specimen was removed from the ECPP after the flight and the results of its examination may be found in the 74-48 experiment reports.

An examination of the ECPP and telemetry recorder after the flight indicated that 18 seconds after the melting of the specimen had been accomplished, a connection opened in the wire to the emitter one of the three power transistors in the R.F. power generator thereupon causing the power supplied to the specimen to decrease by 33%. Further examination also revealed that the water flow was inadequate through the branch of the cooling system which removes heat from the R.F. power generator. This was indicated by a steady, rapid rise in the temperature of the copper heat sink upon which the power transistors were mounted. At 215 seconds the temperature of the heat sink was 89°C, which is greater than the maximum service temperature of the plastic tubing. At 260 seconds, [illegible]0 seconds after the specimen had solidified, the temperature was about 106°C and the pressure in the weakened tubing caused it to rupture suddenly at the heat sink output connection.

The experiment probably continued to function normally but after 30 seconds the telemetry data were so badly affected by moisture within the ECPP that nothing further could be determined from the telemetry after 260 seconds. It is known, however, that the two remaining power transistors in the power generator continued to overheat until they were damaged. The surge current through them apparently exceeded the contact fuzing current rating of the power contactor as it was still closed after the ECPP was recovered.

The experiment 74-48 was successfully completed despite the occurrence of the failures noted above.

5.0 ISSUED DOCUMENTS APPLICABLE TO THE ECPP

95M17100	Electromagnetic Containerless Processing Package (ECPP) - Top Assembly Drawing
SSL-ECPP-004	ECPP Environmental Test Plan
SSL-ECPP-006	ECPP Electromagnetic Interference Control Plan
SSL-ECPP-007	ECPP Functional Test Plan
SSL-ECPP-008	Preparation Procedure for the ECPP Battery
SSL-ECPP-009	ECPP Interface Control Document
SSL-ECPP-010	ECPP Qualification Test Data
ECPP-006-01	EMI Test Report

6.0 REFERENCES

1. Field Management for Weightless Containerless Processing, General Electric Co., Contract NAS8-24683, Final Report.

2. Free Suspension Processing Systems for Space Manufacturing, General Electric Co., Contract NAS8-26157, Final Report, June 15, 1971.

3. Electromagnetic Containerless Processing Requirements and Recommended Facility Concept and Capabilities for Space Lab, General Electric Co., Contract NAS8-29680, Final Report, May 13, 1974.